ABSTRACT

The ground surface above the center of oil production subsided about 9 meters over 27 years. Most observers related subsidence to compaction in the oil reservoirs caused by fluid production and pore pressure reduction.

Axial loading tests on the reservoir sands and shales (siltstones) show the sands to be either as or more compactable than the shales. Reservoir calculations, oil well casing measurements, and laboratory tests, indicated a reduction as great as three to four percent in the bulk sand volumes (about 10-11% of the pore volume). It is concluded that most of the compaction prior to 1952 occurred in the reservoir sands. Compaction percentage calculations place 32.4 percent of the cumulative compaction in the shales and 67.6 percent in the sands.

Water injection programs arrested subsidence and caused elastic rebound, which in conjunction with pump pressures has uplifted the surface as much as 33.5 cm over 8 years. Rebound is believed to be confined principally to the sand intervals. The coefficient of rebound is estimated to be .005/unit of vertical sand thickness; of which only about 50 percent is seen at the surface due to unrelieved stresses in the overburden.

RÉSUMÉ

Le sol au-dessus du centre de la zone productrice s'est affaissé d'environ 9 mètres en 27 ans. La plupart des spécialistes ont attribué cette subsidence à la compaction du réservoir due à la réduction de pression dans les pores résultant de l'enlèvement du fluide.

Des essais de compression triaxiale sur les sables et les argiles de la formation productrice ont montré que les sables étaient autant, ou plus, compressibles que les argiles. Les calculs de réservoirs, les mesures sur les tubages, et les essais de laboratoire, ont indiqué une réduction de 3 à 4 % du volume total des sables (environ 10-11 % du volume des pores). Il en a été conclu que la majeure partie de la compaction antérieure à 1952 s'est produite dans les sables du réservoir. D'après les calculs effectués, 32,4 % de la compaction cumulée sont attribuables aux argiles, et 67,6 % aux sables.

Les programmes d'injection d'eau ont arrêté la subsidence et provoqué une expansion élastique qui, en conjonction avec la remontée de la pression, a rehaussé la surface de 33,5 cm en huit ans. On pense que l'expansion est limitée principalement aux intervalles sableux. Le coefficient d'expansion est estimé à 5/00 (5 pour mille) de l'épaisseur verticale des sables; mais la moitié seulement de cet effet est visible en surface, en raison de la pression maintenue par la couverture.

INTRODUCTION

Wilmington Oil Field is located in the southern part of California, U.S.A. in the physiographic area known as the Los Angeles sedimentary basin (fig. 1). Approximately 35 fields produce from sandstone reservoirs of Upper Miocene and Pliocene ages. Surface subsidence has occurred in minor amounts (1 meter or less) over several of these fields. The extreme case and most publicized is that of Wilmington Oil Field located in and near the City of Long Beach. World-wide attention has been attracted to his area because of it's location in the center of a highly industrialized port and naval shipyard (fig. 2).

Cumulative subsidence had reached 9 meters in 1968, at the center of an elliptical shaped surface depression, before compaction was controlled in the oil reservoirs by water injection. Differential horizontal movements as great as 3 meters accompanied...
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the vertical subsidence, causing extensive damage to wharves, pipe lines, buildings, streets and bridges, necessitating costly repairs and surface filling (fig. 3 and 4).

Figure 1.

CAUSATION AND LOCATION OF COMPACTING STRATA

During the period from about 1948 to 1958, when the surface was sinking at rates from 30 to 65 cm/per year, many investigative reports were written as to causation and many predictions made as to the ultimate subsidence.

The first two comprehensive studies were made by Gilluly, Johnson and Grant [6] and by Harris [8] in 1945. Both of these reports surveyed possible causes, including
ground water withdrawals and tectonic movements, related subsidence to compaction in the oil zones, theorized as to the mechanics of compaction, and predicted a maximum subsidence of about 3 meters. Gilluly et al. concluded that the compaction was occurring within the fluid producing sands, while Harris concluded that it was the shale members within the oil zones which were compacting. This controversy as to the mechanism of compaction has not been resolved and still has proponents for both viewpoints.
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**LOCATION OF COMPACTING STRATA**

During 1948-1949 while there still existed some doubt regarding the depth of the compacting strata as well as the mechanics of compaction, a method was developed for locating and estimating compaction by measuring the deformation in oil well casing [11]. This procedure, called collar counting, is as follows:

1. Locate the recessed area between coupled casing joints in oil wells with a magnetic locator connected to a vernier cable odometer at the surface;
2. Determine casing joint lengths by the difference between collar locations;
3. Compare these joint lengths with accurate surface measurements or a prior collar survey.

Casing joints of about 14 meters in length were found to be vertically shortened as much as 36 cm (fig. 5). Based on the casing compression data from collar counting, most observers since 1949 have conceded that compaction was localized in the four uppermost oil producing zones.

**JOINT LENGTH DIFFERENCE BETWEEN CASING TALLY AND MEASUREMENT**

![Figure 5.](image)

**PREREQUISITES FOR SUBSIDENCE**

The consensus of most authorities from many disciplines is that the extraction of reservoir fluids and the consequent lowering of pressures caused reservoir compaction and surface subsidence regardless of whether the compacting strata were primarily sand or shale.

Accepting the above consensus as factual, three statements of condition can be made which are axiomatic for Wilmington type subsidence. These are:

1. Reservoir fluid pressures must be lowered;
2. The reservoir rocks must be compactable (uncemented) and unable to effectively resist deformation upon a transfer of load from the fluid phase to the grain to grain contacts;
3. The overburden must lack internal self support and be of such a nature as to easily downward and supply a constant load to the underlying formations.
PREDICTIONS

Along with the reports on the causes of subsidence, there were many predictions made as to the maximum amount which might be expected. These estimates ranged from about 3 meters to over 23 meters, dependent upon the date when the prediction was made. In general it may be said that accurate extrapolations based on known conditions and cause and effect relationships were not made until 65 or 75 percent of the probable total subsidence had occurred. Two accurate extrapolations are shown on figure 6, both of which were heavily weighted to an historical base [3 and 13]. The Law extrapolation assumed no injection influence while the Branson extrapolation did.

MECHANICS OF COMPACTION

Many of the basic mechanics of compaction are related to formation stability which involves geological structure, sand sizing, composition, cementation and shale induration and competency. Following is a brief summary of these characteristics in the Wilmington field:

The structure is a tension faulted anticline about 17 kilometers long with a span of about 4.7 kilometers. The beds are nearly flat or dip gently for about 1.6 kilometers across the crest. The sands are composed of about 35 to 70 percent quartz, 12 to 40 percent feldspars and 8 to 12 percent silt and clay minerals. Porosities range from about 25 percent at 1500 meters to 35-40 percent at 700 meters. Above 1200 meters the sands are uncemented and loose and grade in grain size from fine to coarse. Below 1200 meters there is an increase in cementation and the degree of induration.

Wilmington shales are usually termed siltstones by soils engineers. Below 1200 meters they are indurated and appear to have good structural strength. Toward the surface the shales become progressively softer and grade to clay. The siltstones and sand layers are intercalated and often do not have a sharply discernible boundary.

The vertical section is divided into seven oil producing zones or intervals for convenience of production based on reservoir characteristics and oil-water interfaces [15].
LABORATORY TESTS

Axial loading tests were made on sand and siltstone cores by various engineering firms including both petroleum and soils specialists. The averaged results of these tests are compared with data from textbook examples [9], Lake Maracaibo [18] and deep water wells in California [10] on figure 7. Wilmington sands above 4000 feet (about 1219 meters) fall in a trend with a silt from a California water test well at 1345 feet (410 meters), a Lake Maracaibo sample from 3100 feet (945 meters) and a textbook example of a very loose sand. The siltstones show an increasing preconsolidation with depth. The deeper samples agree generally with the Lake Maracaibo “clay sample”. The preconsolidation break [9] in the void ratio versus pressure curves is seen fairly well in the siltstones but not in the sands due to their unconsolidated nature. All of the tests show that the unconsolidated sands compact easily by grain rearrangement, possible crushing of grain points and plastic flow of softer materials when subjected to loading. The recovery cycle of these tests (unloading) shows a small portion of the compaction to be elastically recoverable. The siltstones in the shallow zones compacted readily when subjected to pressures higher than preconsolidation. Siltstones from below 3100 feet

![Diagram of void ratio vs. applied pressure](image)

**FIGURE 7.**

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(942 meters) compacted a lesser amount of which a large percentage was elastically recoverable, indicating a strong internal structure. Siltstone permeabilities are 1/10,000 or less than that of the sands, which, in conjunction with a stronger internal structure, makes a rapid consolidation unlikely.

FIELD MEASUREMENTS

Collar logging results from Well W-2 are summed by years and by oil zone on figure 8. (For zone depths refer to fig. 9.) These data show a rapid compaction in the Upper Terminal zone to about 1952 with a lesser but similar pattern in the Ranger zone. It is here assumed that a rapid compaction rate is indicative of primarily sand compaction.

SUMMATION OF JOINT LENGTH CHANGES
BY ZONE – COMBINED TO NEAREST JOINT

WELL W-2

![Graph of summation of joint length changes by zone](image)

This can be verified by observing the data on figure 9. Casing compression data from two nearby wells are compared with their electric logs which enable the primarily shale and sand intervals to be observed. From 1945 to 1965 the data from Well W-2 show that most of the compaction occurred in the sand intervals. Well W-279 data from 1959 to 1965 show that most of the compaction occurred in the shale intervals. (Note scale difference).

CALCULATIONS

Theoretical sand compaction can be calculated from the average sand curve on figure 7, using the following expression: \( \Delta H = \Delta e/1+e \times H \) where: \( \Delta H \) = change in thickness, \( \Delta e \) = change in void ratio between varying loads, \( e \) = original void ratio, \( H \) = original interval thickness. Applying this formula to a total compactable sand thickness of about 242 meters in the upper four zones and using an average pressure reduction of 93 kg. sq. cm (at a depth of 913 meters), \( \Delta H \) = about 10.2 meters. Using this same equation and appropriate pressure and depth ranges for the shales, a theoretical shale compaction of 6 meters is calculated, giving a total of 16.2 meters of theoretical compaction in the upper four zones. Subsidence rate decline curves indicated a maximum subsidence might be about 10.7 meters. The zone compaction data shown in figure 8 were proportionally adjusted to reflect the actual surface subsidence of about
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ELECTRIC LOG AND CASING COMPRESSION COMPARISON
NEAR CENTER OF MAXIMUM SUBSIDENCE

Well W-2
11-45 TO 3-65

Well W-279
3-59 TO 3-65

FIGURE 9.

9 meters and are listed in the table below. By using the changes in the rate of compaction in figure 8 as a guide to the relative contribution of the sands and shale to compaction, the following percentages were calculated:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Shale</th>
<th>Sand</th>
<th>(Sand%)</th>
<th>Compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tar</td>
<td>27 cm</td>
<td>63 cm</td>
<td>(70.0%)</td>
<td>90 cm</td>
</tr>
<tr>
<td>Ranger</td>
<td>162 cm</td>
<td>153 cm</td>
<td>(48.6%)</td>
<td>315 cm</td>
</tr>
<tr>
<td>U. T.</td>
<td>72 cm</td>
<td>333 cm</td>
<td>(82.2%)</td>
<td>405 cm</td>
</tr>
<tr>
<td>L. T.</td>
<td>30 cm</td>
<td>60 cm</td>
<td>(66.7%)</td>
<td>90 cm</td>
</tr>
</tbody>
</table>

(Surface subsidence)

Compaction factors (unit of compaction/unit of sand or shale)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tar</td>
<td>.007 + .015 = .022</td>
</tr>
<tr>
<td>Ranger</td>
<td>.013 + .039 = .052</td>
</tr>
<tr>
<td>U. T.</td>
<td>.014 + .029 = .043</td>
</tr>
<tr>
<td>L. T.</td>
<td>.014 + .013 = .027</td>
</tr>
</tbody>
</table>

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Total compaction percentage calculations place 32.4% of the compaction in the shales (siltstones) and 67.7% in the sands. The above table of compaction factors show the bulk volume of the sands to be reduced in a range of about 1 to 4 percent, all of which is at the expense of reservoir porosity.

MECHANICS OF REBOUND

The concept that a partial restoration of depleted reservoir pressures will lift a thousand meters of overburden can be difficult to grasp. Supporting data connecting surface rebound with repressuring is found in both laboratory loading tests and practical oil field measurements.

LABORATORY TESTS

All samples tested (fig. 7) exhibited a small rebound (expansion or swelling) during the unloading cycle. The swelling portion of these curves is normal for earth materials tested in this manner and is generally considered to be due to the elastic properties of the samples.

FIELD MEASUREMENTS

Surface response to water injection was measured in 1961, shortly after large scale injection was commenced into the oil reservoirs (fig. 10). The bench marks shown are located in various areas and show differing times of injection response. Elevation is gained and lost by the bench marks in step with the water injection rate. Figure 11 illustrates movements of a bench mark relative to changes in reservoir pressure. Rebound is directly related to changes in reservoir pressure and only indirectly to water injection rate; however, pressure data usually are not as readily available. Total rebound over the entire area is shown in figure 12. The maximum rebound recorded through 1968 was 33.5 cm.
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The collar count technique was also used to measure zone expansion (fig. 13) in areas of high water injection rate. Some casing joints indicate an elongation more than that theoretically possible without parting in the threaded ends.

Because of the rapid surface response to injection rate, rebound is qualitatively judged to be confined to the sand intervals. Supporting this premise is the obvious difficulty which would be experienced moving water into the low permeability shales with their relatively high pore pressures versus the ease with which water enter the sands because of their higher permeabilities and lower pore pressures. Some rebound might be generated in the shales given a large number of years but the amount is considered to be insignificant.

The area adjacent to an injection well bore is at a considerably higher pressure than the average pressure in the reservoir. This pressure, which is much greater than hydrostatic, hydraulically lifts and supports the surface in excess of normal elastic rebound.

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**Figure 11.**

**Figure 12.**
About 6 cm of rebound are attributed to this mechanism, all of which is considered to be highly unstable and subject to rapid loss.

**ESTIMATES OF ULTIMATE REBOUND**

Estimates of ultimate rebound are highly conjectural because of many complicating factors such as the multiplicity of reservoirs, varying production practices and overburden restraint. A rebound factor (unit of expansion per unit of sand being repressured) of .005 was calculated from the unloading cycle of the date on figure 7 using pressure ranges representative of reservoir conditions.

An expansion factor of .004 to .006 per sand unit also was calculated using the expansion of the zones being repressured as indicated on figure 13. At the time these well measurements were made only 40 to 50 percent of the apparent elongation had appeared as surface rebound.

At bench marks 1790 (fig. 10) about 251 vertical meters of reservoir sand are being repressured. Using the expansion factor of .005 and a 50 percent surface response as indicated by collar counting, a surface rebound of 62.7 cm is calculated. This bench mark has currently risen 33.5 cm and is still rising.

At some point in the rebound cycle, surface response may be closer to unity than to 50 percent. This point is believed to be related to the unknown amount of unrelieved stress in the overburden.

Figure 14 is a composite of the subsidence at the center of the subsided area and the maximum rebound which has occurred in the other areas where the zones are being repressured. Ultimate rebound is extrapolated to be about 76 cm, dependent upon
actual repressuring and the percentage of zone rebound which appears at the surface. The rebounded elevations are shown as being unstable and subject to rapid loss if the pressures are reduced.

FIGURE 14.

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**DISCUSSION**

*Intervention of Mr. Joseph F. Poland (USA):*

*Question:*
I believe you have concluded that the compaction has occurred chiefly in the sands. Do you have any evidence as to whether the compaction is primarily by grain rearrangement or by crushing?

*Answer of Mr. Allen:*
We have only our judgement for this, we really do not know. Based on the work, some of which we saw this morning, it appears that you might have some laboratory data now, which we do not have for proposing the crushing of sand grains. We always felt that this was quite obvious because in the arkosic sands which we have in Wilmington, meaning that they are composed at least in part of feldspar, that they are soft and in general they are irregularly shaped. So we feel that when the reservoir pressures are depleted there are irregular transfers of loading, some of which on grain to grain points is quite higher than you might think from the average pressure withdrawn in the reservoir, and that after the primary rearrangement of sand grains and plastic flow takes place, we do feel that we do have shattering, but we have no proof of it.

*Intervention of Dr. James E. Roberts (USA):*

*Question:*
I have heard that during subsidence the upper non producing formation expands about 0.3 ft for each foot of subsidence. Is it true? If it is, was this phenomena considered in your evaluations and computations relating formation compaction with observed surface subsidence?
Answer of Mr. Allen:
That may be correct. I am not sure. The collar count data indicated that there was some expansions in the upper zone but when you get into areas of very small rebound, of tenths of a foot, such as you are speaking of, you are not sure of your data. So, assuming that this happens, the amount was small and we did not take it into account in subsidence. We are speaking only of measured subsidence of the surface related to the oil zones. So it is possible that the compaction of oil zones is greater that what we have actually shown here. These would be minimum figures.

Intervention of Prof. Kenneth E. Lee (USA):

Question:
You mentioned that if the sand has any cementation in it, it will not compact. This does not seem to follow logically. We know that all materials compress under changing load. And I wondered if you had any data from other fields where the material is essentially a cemented material that show definitely that this does not happen?

Answer of Mr. Allen:
I think we are speaking of the difference between qualitative and quantitative here, and what will compact and what any compaction means. There is no question that any material with pores can be compacted when enough load is put on it. There are many studies which have been made on cemented sandstones. I have a bibliography of them, and I believe I used some of them as references in this paper, in which cemented sandstones had been stressed and the deformations measured. Now, when the sandstones are cemented, deformations are found, usually within the elastic range. You find that within the range of pressures, that might be suffered in producing oil field reservoirs, the strains which are imposed normally will not crush a cemented sandstone. They will deform slightly elastically. There is a very slight reduction of pore volume, the amount is perhaps a few percent of what we see by rearrangement of sand grains.

ANALYSIS OF BOREHOLE EXTENSOMETER DATA FROM CENTRAL CALIFORNIA

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Abstract
In subsiding areas of central California, highly sensitive borehole extensometers provide data that define the compression characteristics of the compacting artesian aquifer systems. The extensometer records are combined with hydrographs for the confined and unconfined aquifers to form stress-strain diagrams on which the annual cycles of head decline and recovery generate a series of open loops. Gross compaction, elastic expansion, and net permanent compaction are clearly defined. The average level of preconsolidation stress, the elastic compressibility at lesser stresses, and the much larger plastic compressibility at higher stresses can often be determined from such diagrams. At a given location, these compressibilities may differ by as much as two orders of magnitude. Under favorable circumstances, estimates of the average vertical permeability and average compressibility of the fine-grained strata can be derived.